ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 2 (2010) 1741–1750

Procedia Engineering

www.elsevier.com/locate/procedia

Fatigue 2010

Towards a faster determination of high cycle fatigue properties taking into account the influence of a plastic pre-strain from self-heating measurements

R. Munier[a,b,*], C. Doudard[a], S. Calloch[a], B. Weber[b]

[a]*LBMS EA4325 ENSIETA/UBO/ENIB/Université Européenne de Bretagne, 2 rue F. Verny, 29806 Brest Cedex 9, France*
[b] *ArcelorMittal Maizières Research & Development BP 30320 – F-57283 Maizières-les-Metz Cedex, France*

Received 6 March 2010; revised 9 March 2010; accepted 15 March 2010

Abstract

The high cycle fatigue (HCF) is a major element for a great design of automotive parts. A wide part of the steel sheets for the automotive industry are stamped, sometimes deeply. During this operation, the steel is plastically strained in different directions, so that a good prediction of the fatigue behaviour requires the determination of the fatigue properties of the pre-strained material. Nowadays, the evolution of HCF properties is often neglected. There are two major reasons for this lack. On the one hand, a good finite element simulation of the forming operation to predict pre-strain field is still a difficult task. On the other hand the time dedicated to traditional fatigue test campaigns (e.g. staircase method) to quantitatively identify this influence is prohibitive. To determine faster this influence, it is proposed to use self heating measurements under cyclic loadings. To illustrate this approach, different pre-strain paths are studied: shear and tension. Finally, a model taking into account the influence of pre-strain on high cycle fatigue properties is proposed and identified from self-heating measurements. The validation of the proposed approach is obtained by predicting S/N curves for pre-strain to 20% of a dual phase steel.

Keywords: steel sheets, fatigue life, probabilistic approach, two-scale model, plastic pre-strain;

1. Introduction

The parts of the structure and the chassis frame of a car are designed by taking into account the Low Cycle or High Cycle Fatigue mission. Concerning the high cycle fatigue regime, parts obtained from steel sheets are subjected to primary forming operations (stamping, bending …). During these drawing operations, the steel is sometimes severely strained according to different directions or strain paths inducing thickness and cumulated plastic strain variations [1]. In other words the material has changed and its current fatigue properties are no more the same as initial ones. For example, traditional fatigue campaigns have been applied to the Dual Phase steel. The S-N curves (Stress-Number of cycles) show that the fatigue properties of the pre-strained material to 20% are higher (Fig. 1(b)) than without (Fig. 1(a)) at a load ratio R=-1 (*i.e.*, without mean stress). The initial endurance limit of 250

* Corresponding author. Tel.: +33 (0)2 98 34 87 13; fax: +33 (0)2 98 34 87 30.
E-mail address: Remi.Munier@ensieta.fr.

doi:10.1016/j.proeng.2010.03.187

MPa becomes 320 MPa after the applied pre-strain. A reliable fatigue life prediction requires thus a good determination of these new fatigue properties caused by the pre-strain.

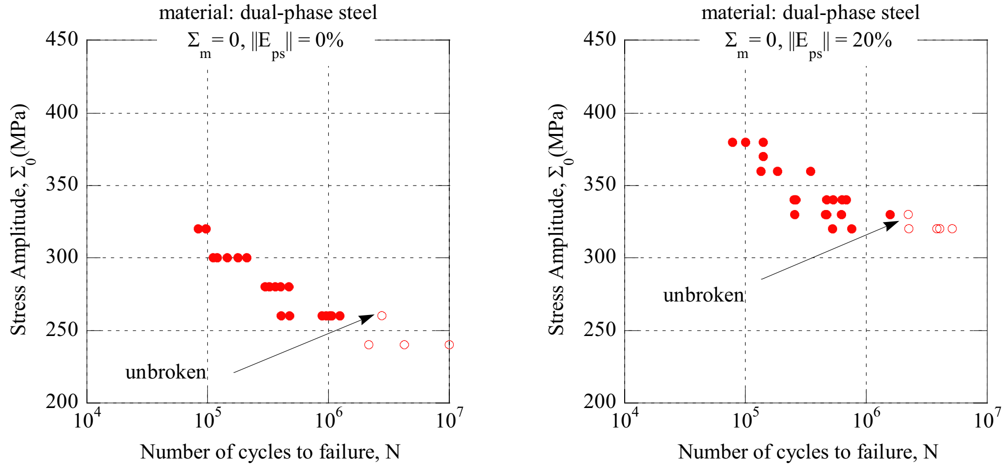

Fig. 1. Results of alternate tension-compression fatigue tests for the studied dual phase steel: (a) without pre-strain, (b) pre-strained to 20%.

Different authors have studied the influence of pre-strain on fatigue properties [2-4]. Nevertheless, the used method (*i.e.*, classical fatigue characterization) is time consuming (one S-N curve requires one month at a loading frequency of 30 Hz) and requires a large number of specimens (25 specimens for one S-N curve). The characterization of the influence of a uniaxial plastic pre-strain would require one S-N curve per plastic strain rate. The number of specimens and the number of hours of test become prohibitive. In this paper, it is proposed to use fast fatigue characterization from self-heating measurements.

For several years, different research teams are working on self-heating measurements [5-9]. This method is based on the evolution of the temperature of a specimen under cyclic loadings. Successive series of loading with a given number of cycles at a given load ratio are applied to the specimen for increasing stress levels. Figure 2(a) shows the temperature elevation for a particular loading level. Macroscopically, the stress level remains lower than the yield stress. At a microscopic scale, microplasticity appears and causes the temperature change. At each level of loading, the steady state temperature elevation can be pointed out and a self heating curve, relating the temperature elevation to the stress level, can be plotted (Fig. 2(b)). To obtain this type of curve, only 90 minutes are required. With a deterministic approach, the mean endurance limit of the material can be determined considering the intersection between the abscissa axis and the asymptote of the self-heating curve [5-6, 10].

More recently, a two-scale probabilistic model has been proposed to link self-heating measurements to high cycle fatigue. These tests permit to identify, not only, the mean fatigue limit, but also the scatter of classical fatigue results [9]. Finally, by using the two-scale probabilistic model and an energetic criterion based on a critical dissipated energy, it is possible to predict the S/N curves for a given probability of failure [10]. It is proposed, in this paper, to extend the previous approach for the analysis of plastic pre-strains on HCF properties.

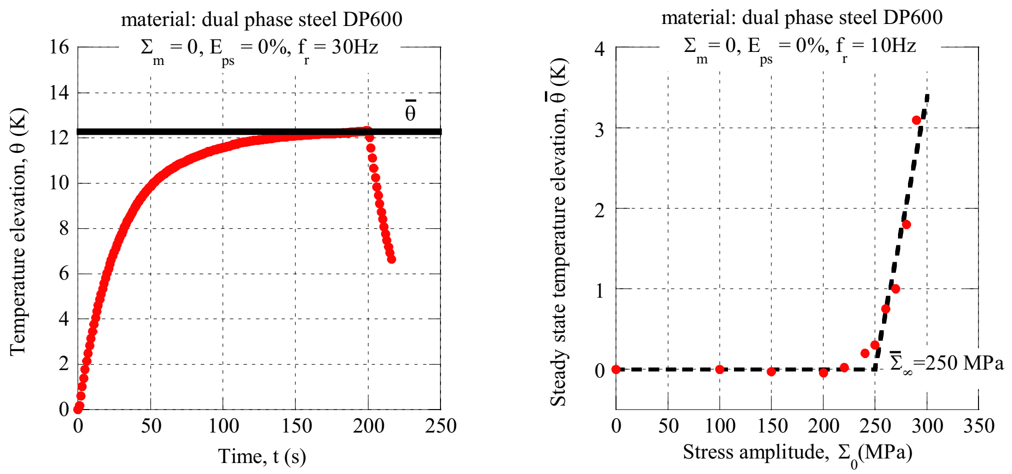

Fig. 2. Self heating measurements under cyclic loadings (f_r = 30Hz) for a dual-phase steel: (a) temperature evolution during 6000 cyclic loadings for the same stress amplitude, (b) change of the steady-state mean temperature with the load amplitude (self-heating curve).

The paper is divided into three main sections. In the first, the different pre-strain paths are introduced. In the second section, the proposed model taking into account the influence of pre-strains on high cycle fatigue properties is presented. It is based on the assumption that microplasticity occurs on sites modelled by a Poisson Point Process (PPP). The third section deals with an identification method and the validation of the proposed approach. The identification procedure is performed from self-heating measurements.

Nomenclature

N	number of cycles
Σ_0	stress amplitude [MPa]
f_r	load frequency [s^{-1}]
Σ_m	mean stress [MPa]
E_{ps}	plastic pre-strain [%]
θ	temperature elevation [K]
$\overline{\theta}$	steady-state temperature elevation [K]
m	Weibull's modulus
$S_0 V_0^{1/m}$	Weibull's parameter [$MPa.mm^{-3/m}$]
β	parameter relating the influence of the plastic pre-strain to the fatigue properties
Δ	dissipation per cycle [$J.m^{-3}$]
$\overline{\Sigma_\infty}$	mean fatigue limit [MPa]
P_f	probability of failure
A	parameter to define the S-N curves [MPa²]

2. Influence of a plastic pre-strain on self-heating measurements

2.1. Presentation of the studied material

The studied material is a ferrite-martensite dual phase steel (approximately 15wt% of martensite) in its hot rolled state. Its chemical composition is given in the table 1. The mechanical properties obtained from monotonic tensile tests on samples (Fig. 3) in the rolling direction are given in table 2. The studied material is characterized by an interesting combination of high strength and good ductility. That is why the dual-phase steels are used in the automotive industry, where this type of properties is required by metal forming process.

Table. 1. Chemical composition (10^{-2}% in mass) of the hot rolled DP600 steel

C	Mn	Si	Cr	Ti	S	Fe
9	100	25	20	1	<0.5	rest

Table. 2. Mechanical properties of the hot rolled DP600 steel

R_e (MPa)	R_m (MPa)	A%
>300	>600	25

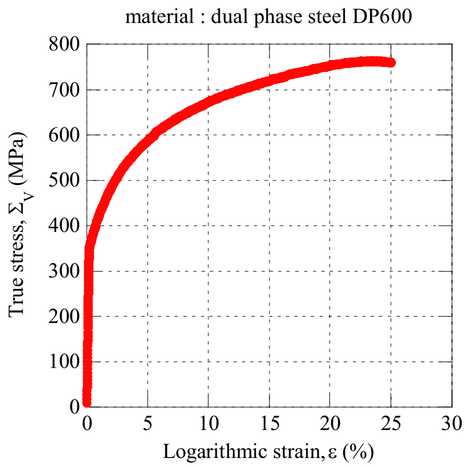

Fig. 3. Behaviour law of the DP600 steel (monotonic tensile test)

2.2. Presentation of pre-strain path conditions

As shown in the introduction, a plastic pre-strain has an influence on the fatigue properties of the steels. Two path conditions are studied for the studied dual-phase steel: tension, shear.

For tension, we can consider specimens with a constant section whose dimensions are given on the figure 4(a). Specimens are strained on a tensile machine with a different level of plastic strain per specimen (here 10% and 15%). To ensure the level of plastic strain that has been reached, digital image correlation is used.

Shear tests were carried out on a rectangular specimen (Fig. 4(b)) [11]. The level of reached strain is controlled by checking the strain of a grid placed in the gauge area. Specimens are cut out by electro-erosion, in order to obtain a uniform level of pre-strain. The machined specimen direction corresponds to the principal stress directions after pre-strain.

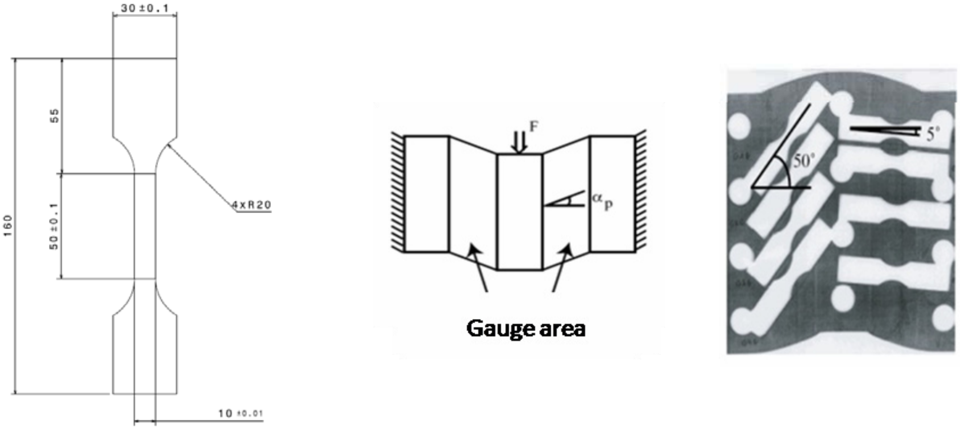

Fig. 4. (a) Dimensions of the specimen used for tension pre-strain; (b) Principle for pre-strain in shearing mode and removing of the specimens for self-heating measurements.

2.3. Self-heating measurements on pre-strained specimens

Self-heating measurements are performed on all the pre-strained specimens with a load ratio R=-1. The self-heating curves obtained for the different pre-strain paths are shown on Fig. 5. In each case the increase of temperature is delayed by the applied pre-strain. This modification corresponds to an increase of HCF properties. Nevertheless, it's necessary to develop a model to link these results to the influence of a plastic pre-strain on HCF properties. This model is presented in the following section.

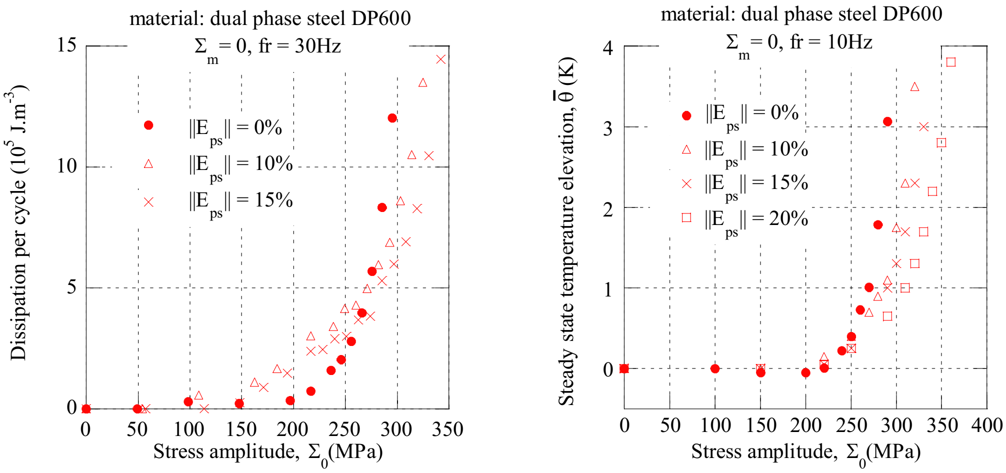

Fig. 5. (a) Self heating curves of a DP600 pre-strained in tension mode; (b) Self heating curves of a DP600 pre-strained in shearing mode

3. A two scale probabilistic model

One of the main goals of the proposed probabilistic two-scale model is to describe, in an unified framework, on the one hand, the self-heating of metallic materials under cyclic loadings at low amplitude for different pre-strains and, on the other hand, the HCF behaviour. It is assumed that HCF damage occurs at the microscopic scale and is caused by microplasticity.

3.1. Activation process of microplasticity

To describe the microplastic activity, it is considered a set of elastoplastic sites of volume V_0, randomly distributed within an elastic matrix. It is then assumed that the microscopic yield stress of sites is a random variable. The distribution of active sites is modelled by a Point Poisson Process (P.P.P.) [12-13]. The mean number of active sites in a Ω domain with a volume V, is then defined by

$$N(\Omega) = \lambda \times V \,, \tag{1}$$

where λ is the intensity of the process. To describe the progressive appearance of microplasticity activation with the applied stress, it is proposed that the intensity follows a power law of the stress amplitude Σ_0,

$$\lambda = \frac{1}{V_0}\left(\frac{\Sigma_0}{S_a\left(\left\|E_{ps}\right\|\right)}\right)^m = \frac{1}{V_0}\left(\frac{\Sigma_0}{S_0\left(1+\beta\left\|E_{ps}\right\|\right)}\right)^m , \tag{2}$$

where m, β, $V_0(S_0)^m$ are three material parameters and $\left\|E_{ps}\right\| = \sqrt{\frac{2}{3}\underline{\underline{E_{ps}}} : \underline{\underline{E_{ps}}}}$ is the von Mises equivalent plastic pre-strain. A linear dependence of pre-strains is introduced to account for the observation of the previous part. To describe the temperature variation induced by the microplastic activity, the elastoplastic behaviour must be defined.

3.2. Elastoplastic behavior of the sites

The relationship between the stress tensor in a site where microplasticity occurs, $\underline{\underline{\sigma}}$ and the macroscopic stress tensor, $\underline{\underline{\Sigma}}$ is given by the localisation law [14-15]

$$\underline{\underline{\sigma}} = \underline{\underline{\Sigma}} - 2\mu(1-\beta_e)\underline{\underline{\varepsilon}}^p , \tag{3}$$

where $\underline{\underline{\varepsilon}}^p$ is the corresponding plastic strain tensor and μ the shear modulus. $\beta_e = \frac{2(4-5\nu)}{15(1-\nu)}$ is given by Eshelby's analysis of a spherical inclusion in an elastic matrix, where ν denotes the corresponding Poisson's ratio.

Microplasticity is described by a yield surface

$$f = J_2\left(\underline{\underline{S}} - \underline{\underline{X}}\right) - \sigma_y \le 0 \,, \tag{4}$$

where J_2 is the second stress invariant, *i.e.*, $J_2\left(\underline{\underline{S}} - \underline{\underline{X}}\right) = \sqrt{\frac{3}{2}\left(\underline{\underline{S}} - \underline{\underline{X}}\right):\left(\underline{\underline{S}} - \underline{\underline{X}}\right)}$, $\underline{\underline{S}} = \underline{\underline{\sigma}} - \frac{1}{3}\,trace\left(\underline{\underline{\sigma}}\right)\underline{\underline{I}}$ is the deviatoric stress tensor, $\underline{\underline{I}}$ the unit second order tensor. A normality rule is assumed and linear kinematic hardening is considered

$$\dot{\underline{\underline{\varepsilon}}}^p = \dot{\chi}\,\frac{\partial f}{\partial \underline{\underline{S}}} \,, \tag{5}$$

$$\underline{\underline{\dot{X}}} = \frac{2}{3}\, C\, \underline{\underline{\dot{\varepsilon}}}^{p} \quad and \quad \underline{\underline{X}}\left(\underline{\underline{\varepsilon}}^{p} = \underline{\underline{0}}\right) = \underline{\underline{0}}\,, \tag{6}$$

where $\dot{\chi}$ is the multiplier plastic and C is the proportionality parameter of the considered hardening [16].

The magnitude of the intrinsic dissipated energy $\delta(\Sigma_0, \sigma_y)$ in a site over a loading cycle is calculated for a given value of the yield stress σ_y

$$\delta(\Sigma_0, \sigma_y) = \frac{4V_0\,\sigma_y}{h}\left\langle \Sigma_0 - \sigma_y \right\rangle, \tag{7}$$

where $\langle\,.\,\rangle$ are Macauley's brackets (*i.e.,* positive part of '.'), $h = C + 3\,\mu\,(1-\beta_e)$.

3.3. Description of the self-heating test

With the proposed framework, the calculation of the global cyclic dissipative energy can be performed by integration over the whole population of active sites

$$\Delta = \int_0^{\Sigma_0} \delta\left(\Sigma_0, \Sigma\right)\frac{d\lambda\left(\Sigma_0\right)}{d\Sigma} V\, d\Sigma = \delta\,\frac{\left(\Sigma_0\right)^{m+2}}{\left[S_0\left(1+\beta\left\|E_{ps}\right\|\right)\right]^{m}}\,, \tag{8}$$

with δ a parameter that depends on the material. To evaluate the corresponding self-heating, this dissipation is introduced in the following heat conduction equation ("0D" approach)

$$\dot{\theta} + \frac{\theta}{\tau_{eq}} = S_t = \frac{f_r \Delta}{\rho C} = \frac{f_r \delta}{\rho C}\,\frac{\left(\Sigma_0\right)^{m+2}}{\left[S_0\left(1+\beta\left\|E_{ps}\right\|\right)\right]^{m}}\,, \tag{9}$$

where τ_{eq} is a characteristic time depending on the heat transfer boundary conditions [10], ρ the mass density, C the specific heat and f_r the loading frequency. The mean stabilized temperature is then given by

$$\bar{\theta} = \frac{f_r \tau_{eq} \delta}{\rho C}\,\frac{\left(\Sigma_0\right)^{m+2}}{\left[S_0\left(1+\beta\left\|E_{ps}\right\|\right)\right]^{m}} \tag{10}$$

3.4. Description of S/N curves

In order to describe the fatigue limits, the weakest link theory is used. It leads to consider that rupture will append as soon as one site will become active. With the proposed framework, the probability to find k active sites into the volume V follows a Poisson distribution

$$P_k\left(V\right) = \frac{\left(\lambda V\right)^k}{k!}\exp\left(-\lambda V\right) \tag{11}$$

The probability of failure which corresponds to the probability to obtain at least one active site into the volume, is then given by

$$P_F = 1 - \exp\left(-\frac{V}{V_0} \left(\frac{\Sigma_0}{S_0 \left(1 + \beta \left\| E_{ps} \right\| \right)} \right)^m \right) \tag{12}$$

The fatigue limits are often characterized by the mean fatigue limit $\overline{\Sigma}_\infty$ and the standard deviation given by, respectively

$$\overline{\Sigma}_\infty = S_0 \left(1 + \beta \left\| E_{ps} \right\| \right) \left(\frac{V_0}{V} \right)^{\frac{1}{m}} \Gamma\left(1 + \frac{1}{m} \right), \tag{13}$$

$$\overline{\overline{\Sigma}}_\infty = S_0 \left(1 + \beta \left\| E_{ps} \right\| \right) \left(\frac{V_0}{V} \right)^{\frac{1}{m}} \sqrt{\Gamma\left[1 + \frac{2}{m} \right] - \Gamma^2\left[1 + \frac{1}{m} \right]}, \tag{14}$$

where $\Gamma(p) = \int_0^\infty t^{p-1} \exp(-t)\, dt$ is the gamma function. Equations (13) and (14) account for volume effects associated to the Weibull model [17-18], and the influence of a pre-strain on fatigue limits.

By using a criterion based on the dissipative energy, the description of the fatigue life of the material is available. The hypothesis lies on the fact that once the dissipative energy has reached a limit, it leads to the failure of the specimen. The number of cycles to failure (*N*) is then related to the stress amplitude by

$$N = \frac{A}{\Sigma_\infty(P_F) \langle \Sigma_0 - \Sigma_\infty(P_F) \rangle} \tag{15}$$

where *A* is a material parameter determined and $\Sigma_\infty(P_F)$ the fatigue limit for a given failure probability defined by

$$\frac{\ln(1 - P_F)}{\ln(1 - 0.5)} = \left[\frac{\Sigma_\infty(P_F)}{\Sigma_\infty(0.5)} \right]^m, \tag{16}$$

with $\Sigma_\infty(0.5) = \overline{\Sigma}_\infty \left[\ln(2)^{1/m} / \Gamma\left(1 + \frac{1}{m} \right) \right]$.

In the further part, the identification procedure is shown. The validation of the model is then illustrated by predicting S/N curves for different pre-strains of a dual-phase steel.

4. Identification Procedure and Validations

4.1. Method of identification

The identification of the 4 parameters of the model previously presented, that is to say $V_0 S_0^m$, m, β and A, is based on the use of self-heating measurements. These tests are made for different load ratios and are led to the rupture of the specimens for the last level of stress [9]. Figures 6(a) and 6(b) illustrate the identification of the parameters in the case of the DP600 steel. The identified values are given in the table 1.

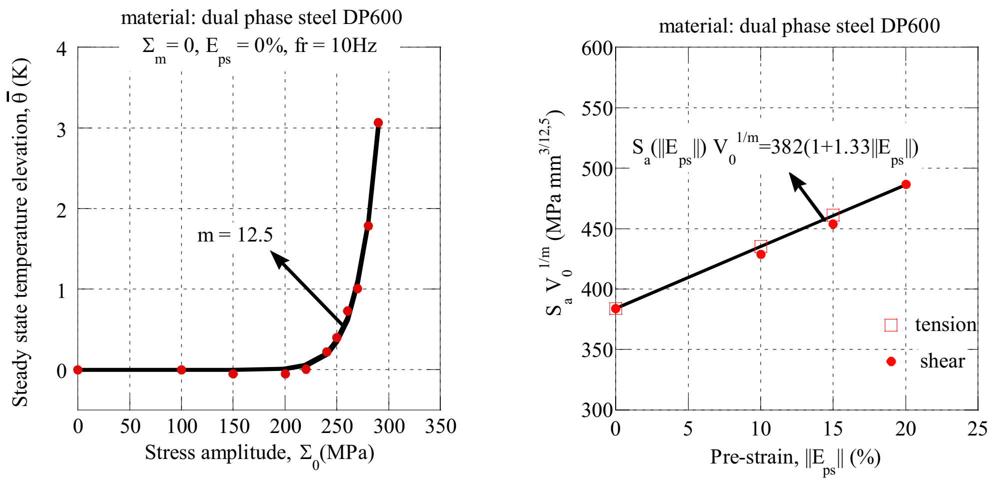

Fig. 6. Identification of the parameters of the model for the studied dual-phase steel from: (a) self-heating curve for E_{ps}=0%, (b) self-heating tests for different pre-strains.

Table 3. Parameters for the dual-phase steel.

m	β	$V_0^{1/m} S_0$	A
12.4	1.33	382 MPa.mm$^{3/12.4}$	1600 GPa²

4.2. Validation

Figure 7(a) shows the good reliability of the model predictions with the experimental results of classical fatigue campaigns for the studied dual-phase steel without pre-strain. The use of self-heating measurements and the two scale probabilistic model allows the characterization of the fatigue properties of this material.

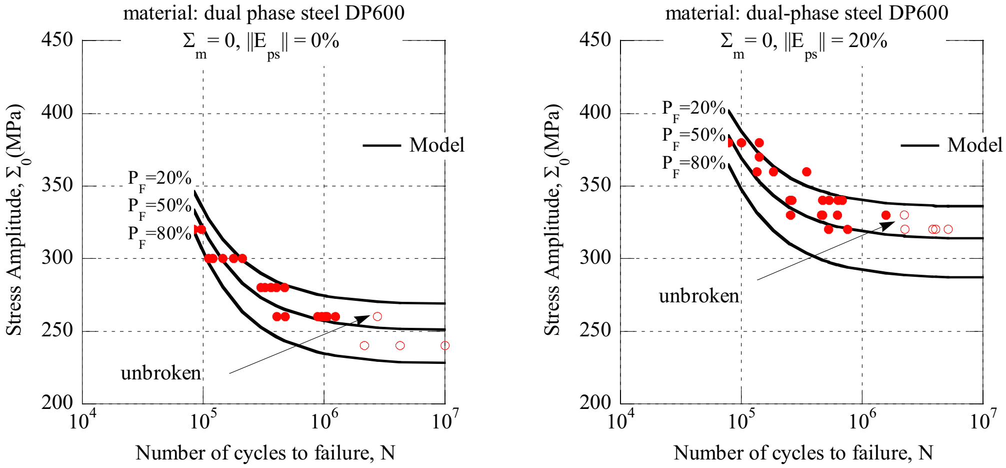

Fig. 7. Comparison between model predictions and experimental results of classical fatigue campaigns for the studied dual-phase: (a) without pre-strain, (b) with a pre-straining of 20%.

In order to validate the prediction of the influence of pre-strains on HCF properties, traditional fatigue campaign is performed with pre-strained specimens at a level of 20%. The figure 7(b) shows that the model predictions are in good agreement with experimental results.

5. Conclusions

Traditional fatigue test campaigns are time consuming and require a large number of specimens for the determination of the influence of parameters as a pre-strain on the fatigue properties. Self-heating measurements represent a good alternative to take into account these influences. Only 90 minutes are necessary to obtain a self-heating curve which authorizes the multiplication of the number of pre-strain paths.

A two scale probabilistic model has been presented to link the self-heating properties to HCF properties. This approach is based on a Poisson point distribution of the sites where microplasticity occurs. With the proposed choice of the intensity of the Poisson point process, a good description of the influence of a pre-strain on HCF properties and self-heating measurements is obtained.

All the parameters of the model have been identified by using self-heating measurements. Finally traditional fatigue test campaign has been performed to validate the proposed approach.

References

[1] M. L. Facchinetti , B. Weber , C. Doudard , S. Calloch, Coupling of Forming Process and Fatigue Design Computations: A Local Approach, *Adv. Eng. Mat*., vol. **11**, 2009, p. 736-741.

[2] G. Z. Libertiny, T. H. Topper, et B. N. Leis. The effect of large prestrains on fatigue. *Exp. Mech*., vol. **17**, 1977, p. 64-68.

[3] T. Uemura. A fatigue life estimation of specimens excessively prestrained in tension. *Fat. Fract. Eng. Mat. Str*., vol. **21**, 1998, p. : 151-158.

[4] D. B. Lanning, T. Nicholas, G. K. Haritos, Effect of plastic prestrain on high cycle fatigue of Ti–6Al–4V*, Mech. of Mat*., Vol. **34**, 2002, p. 127-134.

[5] M.P. Luong, "Infrared Thermography of Fatigue in Metals," *SPIE*, vol. **1682**, 1992, p. 222-233.

[6] G. La Rosa et A. Risitano, "Thermographic Methodology for Rapid Determination of the Fatigue Limit of Materials and Mechanical Components," *Int. J. Fat.*, vol. **22**, 2000, p. 65-73.

[7] A. Galtier, O. Bouaziz, et A. Lambert, "Influence de la Microstructure Des Aciers sur leurs Propriétés Mécaniques," *Mécanique et Industrie*, vol. **3**, 2002, p. 457-462.

[8] P. K. Liaw, H. Wang, L. Jiang, B. Yang, J. Y. Huang, R. C. Kuo and J. C. Huang, Thermographic detection of fatigue damage of pressure vessel at 1 Hz and 20 Hz*, Scripta Materialia*, vol. **42**, 2000, 389-395.

[9] C. Doudard, S. Calloch, F. Hild, P. Cugy, et A. Galtier, "Identification of the scatter in high cycle fatigue from temperature measurements," *C.R. Mecanique*, vol. **332**, 2004, p. 795-801.

[10] C. Doudard, S. Calloch, P. Cugy, A. Galtier, et F. Hild, "A probabilistic two-scale model for high-cycle fatigue life predictions," *Fatigue & Fracture of Engineering Materials & Structures*, vol. **28**, 2005, p. 279-288.

[11] P. Genevois, "Etude expérimentale et modélisation du comportement plastique anisotrope de tôles d'acier en grande déformations, PhD Thesis, Institut National Polytechnique de Grenoble, France, ,1992.

[12] R. Gulino et S.L. Phoenix, "Weibull Strength Statistics for Graphite Fibres Measured from the Break Progression in a Model Graphite/Glass/Epoxy Microcomposite," *J. Mater. Sci.*, vol. **26**, 1991, p. 3107-3118.

[13] D. Jeulin, "Modèles morphologiques de structures aléatoires et changement d'échelle," 1991.

[14] M. Berveiller, A. Zaoui, An extension of the self-consistent scheme to plastically flowing polycrystals, *J. Mech. Phys. Solids*, vol. **26**, 1979, p. 325–344.

[15] E. Kröner, On the plastic deformation of polycristals*, Acta Met*, vol. **9**, 1984, 9:155–61.

[16] J. Lemaitre et J.L. Chaboche, *Mechanics of Solid Materials*, Cambridge (UK): Cambridge University Press, 1990.

[17] W. Weibull, "A Statistical Theory of the Strength of Materials," *Roy. Swed. Inst. Eng. Res*., vol. Report **151**, 1939.

[18] W. Weibull, "A Statistical Distribution Function of Wide Applicability," *ASME J. Appl. Mech.*, vol. **18**, 1951, p. 293-297.